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InAs/GaSb Quantum Well Structures for Infrared Detector Applications

by

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Abstract

The detection of MWIR (mid wavelength infrared radiation) is the important for industrial, biomedical and military applications. In certain military applications, it is desirable for the radiation detector to operate in the middle wavelength IR (MWIR) band corresponding to a wavelength band ranging from about 3 microns to about 5 microns. Such MWIR detectors allow for thermal imaging of airplanes, artillery tanks and other objects having a similar thermal signature. In addition, MWIR detectors may be used in low power applications such as in night vision for surveillance of personnel.

Now a day commercially available uncooled IR sensors operating in MWIR region (2 – 5 µm) use microbolometric detectors which are inherently slow. The novel detector of InAs/GaSb quantum well structures overcomes this limitation. However, third-generation high-performance IR FPAs are already an attractive proposition to the IR system designer. They covered such as multicolour (at least two, and maybe more different spectral bands) with the possibility of simultaneous detection in both space and time, and ever larger sizes of, say, 2000 × 2000, and operating at higher temperatures, even to room temperature, for all cut-off wavelengths.

These hetero structures have a type-II band alignment such that the conduction band of InAs layer is lower than the valence band of GaSb layer. The effective bandgap of these structures can be adjusted from 0.4 eV to values below 0.1 eV by varying the thickness of constituent layers leading to an enormous range of detector cutoff wavelengths (3-20µm). This work is focused on the various key characteristics the optical (responsivity and detectivity) and electrical (surface leakage & dark current) of infrared detector and proof of concept is demonstrated on infrared P-I-N photodiodes based on InAs/GaSb superlattices with ~8.5 µm cutoff wavelength and bandgap energy ~150 meV operating at 78 K where supression of surface leakage currents is observed.
Dedicated To My Wife
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Introduction

1.1 Background

Early infrared (IR) imaging systems utilized extrinsically doped Ge as the detecting material. The typical operating temperature of these detectors was 28K. In the 1960s, development of the semiconductor alloys HgCdTe and PbSnTe, with their tunable bandgaps that covered the complete IR spectrum from 1 to 20 µm. In the early 1970s is the first generation of modern high-performance IR systems, with the beginning of the so-called common module, first developed by Texas Instruments. The key point of this system was a simple 180-element linear parallel-scan, HgCdTe photoconductive array, mounted on a cold finger, operating at approximately 77K. The IR image formed at the focal plane of the system was scanned across the simple linear array of detectors by a rotating mirror, thus generating one line of the IR scene at a time, with an available integration time (or noise bandwidth) determined by the system line time, and the image was formatted by the subsequent off-focal plane electronics. This first generation imaging system was thus mechanically complex, but geometrically simple from a detector; hence array producibility was more efficient. The array bias and amplifier electronics were mounted off the cold finger at an elevated temperature [1].

In the 1990s, the second generation of IR systems evolved, in which the detector bias and signal electronics were incorporated onto the cold finger itself. This was typically achieved by hybridizing the IR-sensitive material with the silicon processor. Third-generation high-performance IR FPAs are already an attractive proposition to the IR system designer. They covered such as multicolour (at least two, and maybe more different spectral bands) with the possibility of simultaneous detection in both space and time, and ever larger sizes of, say, 2000 × 2000, and operating at higher temperatures, even to room temperature, for all cut-off wavelengths.

There are four detector technologies that may meet the specifications of third-generation IR systems: multispectral MCT, antimonide-based materials, quantum-well IR photo detectors (QWIPs), and uncooled micro bolometer detectors. Uncooled detectors will probably be used for most low- and mid-level applications in the near future. For example, uncooled focal plane arrays of 640 × 512 pixels in size have been demonstrated. With no cryogenics needed, they are low in cost, lightweight, and compact.
Mercury cadmium telluride technology can not take the form of large-format focal-plane arrays for the long wavelength infrared (LWIR, 8-14 µm) range because the uniformity and operability of such arrays are very poor. Therefore, it is accepted today that MCT will cover the medium wavelength infrared (MWIR, 3-5 µm) range (where the mercury content of the compound semiconductor is lower than for the LWIR). Dual-colour MCT detectors can be made in the MWIR spectral range.
Antimonide-based materials theoretically have great potential (see Fig. 1). They can be tuned in a wide wavelength range, have high quantum efficiency, and cover both the MWIR and LWIR. Mid-wave infrared: 3 to 5 micrometers (defined by the atmospheric window and covered by Indium antimonide [InSb] and HgCdTe and partially by lead selenide [PbSe]). Long-wave infrared: 8 to 12, or 7 to 14 micrometers: the atmospheric window (Covered by HgCdTe and microbolometer). Figure 2, photovoltaic infrared detectors (such as MCT and InSb) are currently available for imaging is several distinct bands, including SW/MWIR (1.5-5.0µm), MWIR (3-5µm), LWIR (7.5-9.5µm) and VLWIR (7.5-11µm).

A successful IR materials technology must be capable of addressing any, and all of these second- and third-generation IR focal plane issues. So the current arsenal of IR materials technologies is examined from a strictly fundamental standpoint, in which the materials and device physics of each situation are allowed to determine the limitations of possible system implementation. This methodology allows for each of the IR technologies to be considered strictly on its fundamental merits, with no diversions, provided by issues associated with a suitable reduction of the technology to practice [1,2].
Chapter 2

Infrared Detector Performance Criteria

The main interest has centred on the MWIR and LWIR range since the atmospheric transmission is the highest in these bands and the emissivity maximum of the objects at $T \approx 300 \text{ K}$ is at the wavelength $\lambda \approx 10 \text{ micron}$. In recent years, there has been increasing interest in longer wavelengths stimulated by space applications.

Infrared detectors fall into two broad categories: photon detectors and thermal detectors. In conventional system photon detector, photons are absorbed and generate free carriers, which are sensed by the electronic readout circuit. In a thermal detector, the incident radiation is absorbed to change the temperature of the material, and the resultant change in some physical property is used to generate an electrical output.
2.1 Photon Detectors

2.1.1 Operating temperature of IR detector

There are two types of photon detector: one is the majority carrier and the other is the minority carrier. If the majority carrier is dominating, then the sensing is the photoconductive in nature. In minority carrier devices, both photoconductive and photovoltaic modes of detection can be utilized. Both parameters of responsivity and noise are typically used to compare the performance of different materials systems and device architectures [5]. The simplest representation of the photon detector is shown in figure 2.1.

![Schematic principle of photon detector](image)

Responsivity is defined as the voltage, or current, signal response of the device to a stimulus of input signal power in the form of a known photon flux. Noise is the inherent fluctuation in voltage, or current, of the device measured on the same node[12] as the responsivity. The primary criterion for responsivity is that it must be large enough to elevate the detector noise floor above that of the signal processing system noise (ie. Pre-amplifier, integrating capacitor, etc). In the case of a simple integrator, the noise on the detector node is determined by the fluctuation of the integrated number of carriers. These carriers can be generated both thermally, within the detector, and by the incident background flux of IR radiation that is absorbed by the detector material. The total number of carriers on the detector node is given by
\[ \Delta N^2 = N_{th} + N_\Phi \]  \hspace{1cm} (2.1)

where \( N_{th} \) is the number of thermally generated carriers, and \( N_\Phi \) is the number generated by the incident background. Equation (2.1) represents the majority carrier photoconductor or the minority carrier photodiode and this is also true for the minority carrier photoconductor, provided that the integration of minority carriers alone is considered. The noise in the minority carrier photoconductor is due to the minority carrier fluctuations, even though the resistivity is controlled by majority carriers [1].

The best possible detector performance occurs when the incoming radiation fluctuation determines the noise of the detector. This regime called background-limited infrared photo detection (BLIP). For the photon detectors BLIP regime occurs when the background photon flux is much larger than the signal flux and is the dominant noise source. In the case of thermal detectors, which depend on temperature change, the incoming optical-radiation fluctuation causes a corresponding equivalent temperature-fluctuation noise that is the lowest noise situation that one can obtain.

For the BLIP requirement

\[ \eta_a \Phi_B > n_{th} \frac{t}{\tau} = G_{th} \]  \hspace{1cm} (2.2)

For an incident background flux, \( \Phi_B \) photons/cm\(^2\)/s, \( \eta_a \) is the absorption quantum efficiency, \( \tau \) is the lifetime of the relevant carrier, and \( t \) is the detector thickness. The photon generation rate per unit area needs to be greater than \( n_{th} \frac{t}{\tau} \), the thermal generation rate per unit area and for \( \eta_a \approx \alpha t \), where \( \alpha \) is the material absorption coefficient, in the requirement of BLIP of \( \Phi_B > n_{th} \frac{t}{\tau} \). Thus, the normalized thermal generation rate is defined as

\[ G_{th}^* = \frac{n_{th}}{\alpha t} \]  \hspace{1cm} (2.3)

and it can be utilized to predict unambiguously the ultimate performance of any IR material and to compare the relative performance of different IR materials as a function of temperature. The normalized thermal generation rate, \( G_{th}^* \), given by Eq. (2.3), thus determines the BLIP operating temperature of any IR material, that is, the temperature below which the IR material has the capability to become background limited, and provides a precise vehicle for comparing different IR materials technologies. For \( \alpha \lambda t >> 1 \), \( \eta_a = 1 \) and maximum absorption efficiency, and hence detector sensitivity, is achieved at the expense of some penalty in increased dark current, and hence requires lower operating temperature for BLIP [1, 5].
2.1.2 Infrared detector sensitivity

In the infrared detector, the most important parameter is absorption quantum efficiency; it is dependent on the characteristics of the IR materials. The absorption quantum efficiency will be lower if the temperature is lower with BLIP[13] and for the specific detector thickness. The overall quantum efficiency of any IR device depends on two factors:

a) The absorption efficiency of incident radiation
b) The transport efficiency of photo generated carriers

The minimum radiant flux that can be measured by different IR detectors with the same responsivity is inversely proportional to the level of total intrinsic noise in the detector. A convenient way to characterize the sensitivity of an IR detector is to specify its noise equivalent power (NEP), a parameter defined as the radiant power incident on the detector that produces a signal equal to the root mean square (rms) detector noise. NEP takes into account both signal and noise parameters of the detector.

\[ \text{NEP} = \frac{i_{\text{noise}}}{R_{\text{responsivity}}} = \frac{\Phi}{i_{\text{signal}}/i_{\text{noise}}} \]  

(2.1.2)

where \( \Phi \) is radiant flux, Watt.

NEP is a convenient parameter to evaluate and compare the performance of IR detectors by predicting the minimum power a given system can detect. However, as shown by eq. (2.1.2), NEP yields the signal-to-noise ratio actually achieved in a given configuration. This information does not allow a direct comparison of the sensitivity of different detector mechanisms or materials.

This can be converted to a noise equivalent irradiance (NEI), which is defined as the minimum observable flux power incident on the system aperture, by renormalizing the incident flux density on the detector to the system aperture area \( A_{\text{opt}} \). The noise equivalent irradiance is given by

\[ \text{NEI} = \text{NE} \Delta \Phi \left[ \frac{A_{\text{d}} h \nu}{A_{\text{opt}}} \right] \]  

(2.1.3)

where the energy \( h \nu \) is monochromatic radiation.

In the noise equivalent temperature difference, radiation received from any object is the sum of the emitted, reflected and transmitted radiation. Real objects emit only the fraction of blackbody radiation, and remaining fraction is either transmitted or, for
opaque objects, reflected. When the scene is composed of objects and backgrounds of similar temperatures, reflected radiation tends to reduce the available contrast. Thermal image arises from temperature variations or differences in emissivity within a scene.

Noise equivalent temperature difference (NETD) expressed in Kelvins, is a parameter characterizing the performance of thermal imaging systems. NETD is defined as the temperature of a target above (or below) the background temperature that produces a signal in the detector equal to the rms detector noise. Thus, it specifies the minimum detectable temperature difference [23]. NETD can be defined for a single detector element or can be averaged for all detector elements in an array.

![Figure 2.2. Comparison between the detectivities of different infrared detector technologies. The background temperature is 300K, the angle of view is 2π steradian [6].](image)

The infrared detector technology, based on MCT alloys, have a currently acceptable operating temperature (78K – 200K) but it posses some serious drawbacks such (i) a sensitive dependence of the energy gap on the alloy composition ratio, requiring a precise control over the growth temperature ($\Delta T = 1 – 5^\circ C$) during the growth (ii) large non-uniformity over large area in LWIR and (iii) large tunnelling currents due to low electron effective mass.
2.2 Thermal detectors

The thermal detector working principle is simple; it is that, when heated by incoming IR radiation, their temperature increases, and the temperature changes are measured by any temperature-dependent mechanism, such as thermoelectric voltage, resistance, pyroelectric voltage [6]. The simplest representation of the thermal detector is shown in figure 2.3.

![Figure 2.3: Schematic principle of thermal detector [6].](image)

The biggest advantage of thermal detectors is their uncooled operation. However, thermal detectors are not useful for high-speed scanning thermal imagers. Microbolometer arrays are used in two-dimensional electronically scanning arrays of uncooled IR sensors.

A bolometer is a temperature sensitive electrical resistor. Its operation is based on its temperature rise causing a change in electrical resistance, which is measured by external electrical circuit. When radiation is removed, the temperature of the bolometer returns to its initial value, which is determined by the ambient surroundings in which it is immersed. If the resistance increases with increasing temperature, the bolometer is said to have a positive temperature coefficient of resistance; if it decreases with increasing temperature, it is said to have a negative temperature coefficient of resistance.

In a thermal detector, the light flux is transformed into heat by absorption (see Fig. 2.3). Now, at most, the absorbed signal power is \( P_s = P_{inc} \), leading to a temperature increase \( \Delta T \) given by:

\[
P_{inc} = H \frac{d}{dt} \Delta T + g \Delta T \tag{2.2}
\]
where $H$ is the thermal mass and $g$ is the thermal conductance of the device. Steady state is obtained after a typical time lag of $\tau = H/g$, and yields a maximum temperature enhancement of $\Delta T_{\text{max}} = SP_{\text{inc}} = P_{\text{inc}}/g$ where $S$ is the sensitivity of the device. Of course, all the technological know-how consists of transforming as much signal into heat, using thermal insulation to prevent leakage, and in transforming the heat into a measurable current or voltage using bolometer with optimized materials, pyroelectric layers. Clearly, optimum design is a complex trade-off between a usable time constant $\tau$ (of the order of 10 s of ms) and a high sensitivity $S$. Impressive (even revolutionary) progress has been achieved in these technologies, thanks to the micro technology appraisal, which will be described in J.L. Tissot’s paper in this issue [7].

The change in temperature of any thermal detector due to incident radiative flux is

$$\Delta T = \frac{\varepsilon \Phi_0}{(G_{th}^2 + \omega^2 C_{th}^2)^{1/2}}$$

Here $\varepsilon$ is the detector emissivity; $\omega$ is the radiant frequency, $s^{-1}$; $\Phi_0$ is the incident radiative flux; $C_{th}$ is the thermal capacity of the detector and $G_{th}$ is the thermal coupling to the detector surroundings. So it is advantageous to make $\Delta T$ as large as possible. To do this, thermal capacity of the detector and its thermal coupling to the heat sink must be as small as possible. The interaction of the thermal detector with the incident radiation should be optimised while reducing all other thermal contacts with its surroundings. This means that a reduced detector size and fine connecting wires to the heat sink are desirable.

The characteristics of the thermal response time for the detector can be defined as

$$\tau_{th} = \frac{C_{th}}{G_{th}} = C_{th} R_{th}$$

Where $R_{th} = 1/G_{th}$ is the thermal resistance.

So the analysing the eqns. 2.2 and 2.4 the trade-off between sensitivity, $\Delta T$, and frequency response is evident. If high sensitivity is required, then a low frequency response is forced upon the detector.
Chapter 3

Infrared Detector Materials

3.1 Electronic Structure of Bulk Materials

A useful way to visualize the difference between conductors, insulators and semiconductors is to plot the available energies for electrons in the materials. Instead of having discrete energies, as in the case of free atoms, the available energy states form bands. Crucial to the conduction process is whether or not there are electrons in the conduction band. In insulators, the electrons in the valence band are separated by a large gap from the conduction band, whereas in conductors like metals, the valence band overlaps the conduction band, and in semiconductors, there is a small enough gap between the valence and conduction bands that thermal or other excitations can bridge the gap (Fig. 3.1.1). With such a small gap, the presence of a small percentage of a doping material can increase conductivity dramatically.

![Figure 3.1.1: Energy bands in solid.](image)

An important parameter in the band theory is the Fermi level, the top of the filled electron energy levels at low temperatures. The position of the Fermi level with the relation to the conduction band is a crucial factor in determining electrical properties. Semiconductor materials have two kinds of band gap, one is direct band gap and another is indirect band gap (Fig. 3.1.3). Also various band gap energies and wavelengths of elementary and binary semiconductor materials are represented in figure. 3.1.2.
Figure 3.1.2 Energy gaps of elementary and binary semiconductor materials compared with the spectral sensitivity of the human eye. Gray bars represent indirect gap semiconductors.
The bandgap in a semiconductor photodiode governs the way the photons of different wavelengths are detected. A simple quantum mechanical model involving two direct gap bands states that the absorption coefficient has a simple dependence on photon energy [29]:

\[ \alpha(\hbar \omega) \approx C \cdot \frac{(\hbar \omega - E_g)^{1/2}}{cm^{-1}} \]  

(3)

The detection can only begin when the photon energy exceeds the bandgap \( E_g \) which in case of a bulk semiconductor is a fixed number. On figure 3.1.3 the bandgap values for some simple and binary compound semiconductors are shown. Alloys of binary compound semiconductors (that are ternary or quaternary semiconductors) provide some flexibility in terms of available bandgap. At the same time a serious limitation comes from the necessity of a lattice-matched substrate for these compounds, since the lattice parameter generally changes with alloy composition. In addition, for most semiconductors the bandgap corresponds to at least visible or near IR light.
3.2 Quantum Structure

In the semiconductor energy bands, for intrinsic semiconductors like silicon and germanium, the Fermi level is essentially halfway between the valence and conduction bands. Although no conduction occurs at 0 K, at higher temperatures a finite number of electrons can reach the conduction band and provide some current. In doped semiconductors, extra energy levels are added. The increase in conductivity with temperature can be represented in terms of the Fermi function, which allows one to calculate the population of the conduction band.

![Diagram of density of states for different dimensionalities](image)

Figure 3.3.3: Density of states (g(E)) for structures of different dimensionalities:

(a) bulk: \( g^{3D}(E) = \frac{m\sqrt{2mE}}{\pi^2\hbar^3} \)  
(b) quantum well: \( g^{2D}(E) = \frac{m}{\pi\hbar^2} \)  
(c) quantum wire: \( g^{1D}(E) = \frac{1}{\pi\hbar} \sqrt{\frac{2m}{E}} \)  
(d) quantum dot: \( g^{0D}(E) = \delta(E - E_n) \) [4].

In the dimensionality of the density of states, an electron in bulk material was represented by a Bloch wave function (atomic position and times a plane wave), and it means that the position of an electron is not determined. So it is clear that the probability of finding the electron anywhere in space is equal. If there is an outer restriction to the movement of the electron, the plane wave description can no longer be used. If the electron motion is restricted to a thin layer, a so called **quantum well**, an envelope function description is used in the direction of restriction (here Z direction).
The resulting wave function is given by equation (3.1), where $C$ is a normalisation constant, $\Phi(z)$ is the quantum well envelop function and $u(r) e^{ik_{x,y}r_{x,y}}$ is the Bloch wave function, where the plane wave is restricted to the x,y-plane.

$$\Psi_{2D}(r) = Cu(r_{x,y,z})\Phi(z)e^{ik_{x,y}r_{x,y}} \quad (3.1)$$

$$\Psi_{1D}(r) = Cu(r_{x,y,z})\Phi(y, z)e^{ik_{r}r_{z}} \quad (3.2)[14]$$

$$\Psi_{0D}(r) = C\Phi(x, y, z)u(r_{x,y,z}) \quad (3.3)$$

The above equation of the character of the wave function will change when reducing the degrees of freedom, and this also has an influence on the density of K-states (K-space reduces from 3D to 0D along with the reduced degree of freedom of the electron). As a result, the density of states also changes with reduced dimensionality [4]. However, the density of states for a bulk semiconductor is proportional to the square root of the energy (Fig. 3.3.3a); The density of states in the 2D case exhibits a step-like behaviour vs the energy (Fig. 3.3.3b) and for 1D and 0D structures, the density of states concentrates to specific energies (Fig. 3.3.3c, d).

### 3.3 Quantum well structures

Electron tunnelling through nanoscale barriers is the most direct consequence of the law of quantum mechanics, for which the Esaki tunnel diode gave most convincing experimental evidence in 1957. Following the evolutionary path of quantum nanostructures, significant milestones are presented, including the birth of semiconductor superlattices, resonant tunnel diodes, quantum wires and dots.

This was perhaps first proposal which advocated engineering a new semiconductor material by applying the principles of quantum theory and used the most advanced crystal-growth techniques of today. The proposal was made to the US Army Research Office (ARO), a funding agency, in 1969. It was daringly stated, but with little confidence in a successful outcome at the time: ‘….. The study of super lattices and observations of quantum mechanical effects on a new physical scale may provide a valuable area of investigation in the field of semiconductors’ [3].
Figure 3.2.1: Absorption and emission of photon energy.

In the quantum processes, quantum properties dominate the fields of atomic and molecular physics. Radiation is quantized such that for a given frequency of radiation, there can be only one value of quantum energy for the photons of that radiation. The energy levels of atoms and molecules can have only certain quantized values. Transitions between these quantized states occur by the photon processes of absorption, emission (Fig. 3.2.1) and stimulated emission. All of these processes require that the photon energy given by the Planck relationship is equal to the energy separation of the participating pair of quantum energy states [8].
3.3.1 Hetero-structures with different layer sequences (band gap Engineering)

![Figure 3.2.2](image)

Figure 3.2.2 a) Quantum well (QW), b) Multiple QW (MQW), c) Superlattice (SL), d) Single barrier tunnelling structure and e) Double barrier tunnelling structure

The bandgap in a semiconductor photodiode governs which the photons of different wavelengths are detected. Detection can only occur when the photon energy exceeds the bandgap $E_g$ which in case of a bulk semiconductor is a fixed number.

A material with novel optical and electronic properties can be obtained when combining different semiconductor materials in so-called hetero-structures [6]. Band gaps are aligned when two different materials are brought together. A band gap alignment can introduce potential barriers and traps for the charge carriers, which cause restrictions of the carrier motion. The band alignment of any heterojunctions can be categorized as type-I, type-II staggered or type-II misaligned. In type-I heterojunction, one material has lower energy for electrons and the holes and therefore both carriers are confined in that layer. In type-II heterojunctions, however, the electrons are confined in one material and the holes in the other. In the special case, which is called type-II misaligned, the energy of the conduction band of one material is less than the valence band of the other one (Figure 3.3.2).

When layered in particular ways, semiconductors can trap conduction electrons in a membrane so thin that, from one face to the other, their behaviour as tiny quantum wave packets takes precedence over their behaviour as particles. This structure is called quantum well, shows in Figure 3.2.2 (a).

A multiple quantum well structure permits substantially uniform injection of carriers from the outside into respective quantum well layers of the multiple quantum well structure (Figure 3.2.2 (b)). A multiple quantum well structure is formed by laminating at least two pairs of quantum well layers each having a thickness substantially equal to the de Broglie's wave-length of electrons and barrier layers with a band gap energy greater than that of the quantum well layers. The multiple quantum well structure is doped with at least one of p-type and n-type impurities in a manner to slope the energy
band of the entire multiple quantum well structure so that injected carriers are distributed uniformly throughout it.

Smith and Mailhiot proposed to use the InAs/GaSb system for the superlattice implementation [13]. The 6.1 Å materials family represented in figure-1 constitutes indeed a privileged platform for the realization of infrared devices. Aluminium antimonide, gallium antimonide and indium arsenide are very closely lattice matched (with $\Delta a/a \approx 0.6\%$) for InAs and GaSb. In addition, these III-V group semiconductors are chemically stable to strong covalent bonds as opposed to the II-VI HgCdTe system with its ionic bonds breaking and liberating Hg at high temperature or during ion implantation.

### 3.3.2 Quantum Well Structure of InAs/GaSb

The InAs/GaSb material system with its broken gap (referred to as type-II) band alignment in a superlattice design, presents numerous advantages over the currently commercialized photo detector systems. The Hg$_{1-x}$Cd$_x$Te system offers one adjustable parameter for the control of the band structure: the part of cadmium x. Instead of using alloys, the idea of a superlattice is to fabricate a stack of alternating thin layers of lattice matched compound semiconductors.

![Figure 3.2.3: Distribution of hole and electron presence probability.](image-url)

Figure 3.2.3 : Distribution of hole and electron presence probability.
In the structure represented on figure 3.2.3(a), the type-II alignment of GaSb and InAs layers form multiple quantum wells for electrons (in InAs) and holes (in GaSb). Adjusting the thicknesses of these layers leads to the change in energy levels. For a certain configuration, the levels of confined electrons in InAs are higher than the levels of the holes in GaSb. The layers are very thin, which leads to coupling between the wells, dislocation of the electron and hole wave functions, splitting of the quantum well levels and formation of artificial conduction and valence bands. The artificial bandgap is not related to the respective bandgaps of InAs and GaSb and consequently, it is possible to engineer materials capable of detecting very long wavelengths. Devices with a cutoff approaching 32 µm have been demonstrated [14].

The quantum confinement and large splitting of heavy-hole and light-hole valence sub-bands in SLs are considered as factors contributing to the suppression of Auger recombination [24, 25]. Moreover, it was found that Auger processes in InAs/GaSb SLs are less sensitive to temperature (power-law dependence of Auger coefficient on the temperature instead of exponential dependence in bulk material [26]). As a consequence, carrier lifetime is increased and quantum efficiency is expected to be higher. Finally, tunneling currents are reduced in the SLs due to larger bandedge effective masses. SLs diode tunneling currents are reduced compared to MCT detectors. This makes SLs attractive for realization of high performance infrared sensors operating near ambient temperature.

However, because the electronic potential is not uniform, the electron and hole function have a spatial correlation. As shown on figure 3.2.3 (b), they are separated. Since the spatial overlap of electron and wave function is smaller than in a conventional bulk semiconductor, the probability of creation of an electron-hole pair under optical excitation is reduced, which constitutes one of the challenges for the type-II materials. Apart from this peculiarity, a type-II superlattice can in the first instance be considered as a bulk semiconductor with a real bandgap [15].
3.3 Quantum well infrared detectors

3.3.1 QWIP

The quantum well infrared photoconductor (QWIP) is a semiconductor infrared photon detector relying on inter-sub-band absorption within either the conduction band (n-type) or the valence band (p-type). The idea of utilizing a quantum well for infrared detection was first presented by Esaki and Sakakii in 1977 and can be explained by using the basic principles of quantum mechanics [1]. QWIPs consist of quantum wells formed by wide-band-gap materials that in bulk do not absorb in the MWIR or LWIR. However, electron (hole) excitation may occur between the ground state and excited states in a conduction (valence) band quantum well (fig. 3.3.1), making intersubband absorption possible in the MWIR or LWIR regions. The quantum well structure is designed so that these photo excited carriers can escape from the quantum well and can be collected as photocurrent. These detectors obtain greater flexibility because the peak and cut-off wavelength can be continuously tailored by varying layer thickness (quantum well width) and barrier composition (barrier height) [5].

![Figure 3.3.1: Schematic of intersubband absorption, which takes place entirely within the valence band (for p-type doping, from H₁ to H₂) or conduction band (for n-type doping, from E₁ to E₂) of a quantum well, respectively [5].](image)

Presently, all superlattice detectors are based on a photodiode design [21]. At cryogenic temperature, the major sources of noise for photodiode are recombination at Shockley-Read-Hall (SRH) centers and surface states. In order to eliminate surface leakage currents, different passivation methods should be involve, such as deposition of relatively thick layer of dielectric material[16], polyamide passivation[17], overgrowth of wide band gap material[18], deposition of passivating sulfur coating electrochemically[19], and from chemical solutions[20]. All of these methods add complexity to the fabrication.
3.3.2 Principle of operation of type-II infrared detectors

The active layers of photovoltaic and photoconductive type-II detectors are made from the super lattices with a type-II band alignment. Similar to a type-I superlattice, the allowed energy states form the ‘minibands’, due to the coupling of electrons and holes in adjacent wells. However, unlike type-I superlattices, one can adjust the bandgap of type-II super lattices from a finite value to virtually zero. These super lattices resemble a direct gap semiconductor, since the minimum of the miniband in momentum space is located at zero. Knowing the band structure and the optical absorption process in type-II super lattices, one can practically use the conventional photo voltaic and photoconductive structures to realize high performance type-II detectors.

Figure 3.3.2: Type-II superlattice InAs/GaSb with effects of strain on band structure.
3.3.3 Features of type-II band alignment and their applications

The special band alignment of the type-II heterojunctions provides three important features that are shown in Figure 3.3.3.

Figure 3.3.3: Unique feature of type-II heterojunctions and superlattices.

These features are used in many devices to improve the overall performance of the device. The first feature is that a superlattice with the type-II band structure can have a lower effective bandgap than the bandgap of each layer. This is an important issue for the application in the mid and long infrared wavelength range, since one can generate an artificial material (the superlattice) with a constant lattice parameter but different bandgap. Recently, very successful detectors [10] and lasers [11] have been implemented in the 2-15 µm wavelength range with InAs/GaInSb superlattices lattice-matched to GaSb substrates.

The second feature is the spatial separation of the electrons and holes in type-II heterojunction. This phenomenon is a unique feature of this band alignment and is due to the separation of the electron and hole potential wells. As a result of such spatial separation, a huge internal electrical field exists in the junction without any doping hydrostatic pressure. High performance optical modulators have been implemented based on this feature [9].
The third feature is the zener-type tunneling in a type-II misaligned heterojunction. Electrons can easily tunnel from the conduction band of one layer to the valence band of the other layer, since the energy of the conduction band of the former layer is less than the energy of the valence band of the later layer. Unlike a zener tunneling junction which requires heavily doped layers, no doping is necessary for such a junction. Therefore, even a semimetal layer can be implemented with very high electron and hole mobility’s since the impurity and ion scattering are very low. This feature of type-II heterojunctions has been successfully used for resonant tunneling diodes (RTDs) and recently for the implementation of type-II quantum cascade lasers [12].
Chapter 4

Sample Structure

The structures were grown on semi-insulating composition of GaSb substrates. First, GaSb buffer layers with a thickness of about 0.1µm were grown directly on the GaSb substrates using a similar set of growth conditions. The growth was optimized for low background doping levels (5X10¹⁶ cm⁻³), and high surface smoothness (~ 15.3 Å roughness) in this layer. The super lattices consist of InAs and Ga0.75In0.25Sb layers at both interfaces and were grown directly on GaSb buffer layers. The growth was terminated by a 0.03 µm GaSb cap layer (Table 4.1) [27].

<table>
<thead>
<tr>
<th>Loop</th>
<th>Layer N</th>
<th>Composition</th>
<th>Thickness</th>
<th>Doping concentration [pMOS]</th>
<th>Name</th>
<th>Other specifications, comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>GaSb</td>
<td>Substrate</td>
<td>—</td>
<td>Substrate</td>
<td>2'' (100)-oriented, EPB=10²⁴ cm⁻²</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>GaSb</td>
<td>0.1 µm</td>
<td>—</td>
<td>buffer</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>GaSb</td>
<td>0.7 µm</td>
<td>3.0E+18</td>
<td>p contact</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>InAs</td>
<td>32.2 Å</td>
<td>n.i.d.</td>
<td>p SL</td>
<td>p SL = no intentional doping</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>Ga₀.₇₅In₀.₂₅Sb:Be</td>
<td>15.3 Å</td>
<td>5.0E+16</td>
<td>p SL</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>InAs</td>
<td>32.2 Å</td>
<td>&lt; 1.0E+18 free carrier concentration@ 77K</td>
<td>n.d. SL</td>
<td>Nominally undoped, n or p type</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>Ga₀.₇₅In₀.₂₅Sb:Be</td>
<td>15.3 Å</td>
<td>n.i.d.</td>
<td>n SL</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>InAs</td>
<td>32.2 Å</td>
<td>5.0E+17</td>
<td>n SL</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>Ga₀.₇₅In₀.₂₅Sb:Be</td>
<td>15.3 Å</td>
<td>n.i.d.</td>
<td>cap</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1: GaSb QWIP #7 growth parameter.

There are three kinds of detector structures are tested, which are the 500 µm X 500 µm (big one, square size), 170 µm² (medium one, circle size) and 90 µm² in all the three samples (Sample 5C, 6F and 7G).
4.1 Mask specifications

The masks were fabricated by Compugraphic according to mask specifications as follows:

The substrate material is SL glass, the dimension is 5” in square, and flatness is 2 μm [27].

<table>
<thead>
<tr>
<th>Layers in gds</th>
<th>Name in L-edit (or masks name)</th>
<th>Type mask</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mesa</td>
<td>Dark</td>
<td>To define mesas for the detectors and test structures</td>
</tr>
<tr>
<td>2</td>
<td>Passivation</td>
<td>Clear</td>
<td>To passivate the edges of the mesas, and also define optical windows and openings for the bottom contacts for the detectors</td>
</tr>
<tr>
<td>3</td>
<td>Contact</td>
<td>Clear</td>
<td>For processing both n (top) and p (bottom) contacts and metal tracks for the detectors</td>
</tr>
</tbody>
</table>

4.2 The Sb – SL single pixel detectors and test structures in chip

There are mainly square and round two types single pixel detectors are included in this design as shown in Fig.4.2. The dimensions of the detectors are varied from 30 μm x 30 μm up to 1000 μm x 1000 μm. The detail geometries of various detectors are listed in table1. These detectors are arranged in an optical active region (6000 μm x 2000 μm) marked as a-area in Fig.4.2 [27].
Fig. 4.3 (a) and (c) show the examples of the square and round detectors, respectively. In fact, with increasing the dimension of the detectors up to 90 \( \mu \text{m} \times 90 \mu \text{m} \), an extra mesa was added to place a metal pad on it for ensuring wire bonding. These detectors were named as B detectors to distinguish with the A-detectors without such pads, which are shown in Fig. 4.3 (b) and (d) for the square and round ones, respectively.

In our former work we discovered that the wire bonding process would be harder if the metal pad on SiN in comparison with the pad on semiconductor materials. In order to compare the dependence of performance on the detector shape directly, the areas with the round and square shapes, for instance (a) and (c), (b) and (d), were set as the same [27].

![Figure 4.3 Different type detectors.](image)

<table>
<thead>
<tr>
<th>Detector shape</th>
<th>Total mesa area (( \mu \text{m}^2 ))</th>
<th>Total top contact area (( \mu \text{m}^2 ))</th>
<th>Optical detection area (( \mu \text{m}^2 )) inside</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square (90 ( \mu \text{m} ))-A</td>
<td>8100</td>
<td>1950</td>
<td>3306</td>
</tr>
<tr>
<td>Square (170 ( \mu \text{m} ))-A</td>
<td>28900</td>
<td>8100</td>
<td>14370</td>
</tr>
<tr>
<td>Square (500 ( \mu \text{m} ))-A</td>
<td>250000</td>
<td>61200</td>
<td>38157</td>
</tr>
</tbody>
</table>
For the components shown in Fig. 3 (a‘) to (d‘), their optical windows are covered by the top contact, which will be used to character the device dark current. Their geometrical parameters are listed in table 4.2. Most of them are arranged in the b-area in the chip, and only the device Square (500 5m)-A is located in the a-area [27].

Table 4.2 Geometrical parameters

<table>
<thead>
<tr>
<th>Detector shape</th>
<th>Total mesa area (µm²)</th>
<th>Mesa perimeter (µm²)</th>
<th>Total top contact area (µm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square (90 µm)-A</td>
<td>8100</td>
<td>360</td>
<td>5256</td>
</tr>
<tr>
<td>Square (170 µm)-A</td>
<td>28900</td>
<td>680</td>
<td>22500</td>
</tr>
<tr>
<td>Square (500 µm)-A</td>
<td>250000</td>
<td>2000</td>
<td>230430</td>
</tr>
</tbody>
</table>

4.3 PIN diode

The single pixel detectors all had a p-i-n design:

Figure 4.5: Schematic of PIN diode (27).
Chapter 5

Experimental Results

The bandgap, the responsivity, detectivity is a non-exhaustive list of information that can be obtained via optical characterization. In this work we only cover spectral quantum efficiency measurements.

5.1 Photo Characteristics

One of the most important issues for detectors with long cut-off wavelengths is the uniformity of the material that is translated to the uniformity of the energy gap. Such uniformity is a crucial requirement for high resolution focal plane arrays (FPA) where the device area can be several square centimeters.

The photocurrent density is given by the total incident photonic flux $\Phi$ and the quantum efficiency:

$$ J_{ph} = \eta q \Phi \quad 5.1 $$

So the total quantum efficiency (QE) of a P-I-N photodiode is the sum of the quantum efficiencies of the p, n and depleted region.

$$ \eta = \eta_n + \eta_d + \eta_p \quad 5.2 $$

The optical signal will be converted into the electrical signal if several conditions are met simultaneously. First, there must be a sufficient generation of carriers at the bulk level which implies that the material has a high absorption. Secondly, the carriers must reach the contacts without recombining. This implies a sufficient big diffusion length (or long diffusion lifetime) for the carriers generated in the doped regions and a strong electrical field in the undoped region. Finally, there must be an efficient extraction of carriers which is possible in the case of ohmic contacts.

$$ \eta_i = (\exp(-\alpha X_n) - \exp(-\alpha (X_n + X_i))) \quad 5.3 $$
This expression does not depend on the p or n side diffusion length because the carriers are extracted from the junction by the electric field before they have the time to recombine. We assume that an air coating matches the air to the superlattice and light is not reflected. The absence of air coating will simply result in a factor \((1 - R)\) before each term. These formulas make clearly appear the trends of the quantum efficiency in diffusion length, un-doped region thickness and absorption coefficient. Of course, the quantum efficiency depends on the considered wavelength because every material has an absorption profile.

5.2 Spectral Response

In the Centre for Quantum Devices, the relative spectral response is measured using a VERTEX 80V Fourier Transform Infrared Spectrometer (FTIR). In this section we discussed the measurement setup for all three samples (sample 5C, 6F and 7G).

VERTEX 80V

The VERTEX 80V vacuum version is based on the new ultrascan interferometer. Active true alignment technology together with the precise linear air bearing ensures continuous and fully optimized performance. The ultrascan interferometer delivers an outstanding peak resolving power. Change of the beam-splitter is effortless since the interferometer is automatically adjusted. Peak quality optics guarantees ultimate spectral range. In addition, the flexibility of the optics bench is unmatched.

Vertex Major Features:

- Innovative True-alignment Technology.
- 21st high throughput designs.
- Spectral resolution better than 0.07 cm\(^{-1}\).
- Resolving power better than 300,000 : 1
- Rapid scan with more than 100 spectral/Sec.
- Widest spectral range from 5 to 50,000 cm\(^{-1}\).
- Peak optics flexibility.
**Fourier Transform Interferometers**

The Fourier Transform is a mathematical formula that allows finding the component frequencies in a complex waveform. By analysing any waveform with the Fourier Transform, the reconstruction of all the waves that went into making it up can be found.

The interferogram can be viewed as being a complex wave, since all of the IR frequencies in the modulator have been added together and then subtracted some through absorption in the sample. By subjecting the interferogram to a Fourier Transform, there is the ability to get back all of the original frequencies, minus those that were partially or totally absorbed by the sample. This is effect; reverse the modulation produced by the interferometer. By creating a graph of the intensity of each frequency, the spectrum of a sample is achieved.

There are several other advantages shared by FTIR instruments over dispersive. One is that, since the IR energy in an FTIR must pass through a beam splitter, only about \( \frac{1}{2} \) of the original IR energy actually strikes the sample. In a dispersive instrument, nearly all of the energy from the source hits the sample. This can cause the sample to warm up and can change its spectrum as a consequence.

FTIR instruments are also naturally immune to stray light, unlike dispersive instruments. The detector on a dispersive instrument can’t distinguish between the IR energy from its IR source and IR that comes from a window, a light bulb or even the spectroscopes’. This extra IR would probably be at the wrong frequency and result in a wrong reading. Because FTIR systems modulate their IR energy, they have no such problem. Any extra light hitting the FTIR detector is interpreted as a DC signal riding on the alternating interferogram. A simple electronic filter can eliminate such signals.

The first function of a FTIR, as for all spectrometers is to analyze the spectrum of an unknown infrared beam. In dispersive instruments this is done e.g. by splitting the beam into quasi-monochromatic components and measuring the intensity of each component. This process is slow and the naturally preferred solution is based on the interferogram measurement.

For a signal extending from negative infinity to positive infinity, the autocorrelation is defined by the following expression. The integral is evaluated for increasing values of \( T \) and the result is averaged. If the average is not taken then the autocorrelation would tend to infinity.

\[
\Gamma(\tau) = \left( \frac{\text{Lim}}{T \to \infty} \right) = \frac{1}{T} \int_{-T/2}^{T/2} S(t)S(t + \tau)dt
\]

If the signal is of finite duration, then averaging it would yield a result of zero. Instead the following definition of the autocorrelation function is used.
\[ \Gamma(\tau) = \int_{-\infty}^{\infty} S(t)S(t + \tau)dt \]

Since the autocorrelation function is even, then the following definition can also be used.

\[ \Gamma(\tau) = \int_{-\infty}^{\infty} S(t)S(t - \tau)dt \]

The Fourier Transform of the autocorrelation function is the power spectrum. So the autocorrelation function and power spectrum form a fourier pair below. The power spectrum removes the phase information from the fourier transform. For random signals the autocorrelation - Power Spectrum pair is the most useful representation. Most spectrum analysers will display either the power spectrum or the magnitude of the transform. In either case, the phase is not displayed.

\[ G(\omega) = \int_{-\infty}^{\infty} \Gamma(\tau)e^{-j\omega\tau}d\tau \]

\[ \Gamma(\tau) = \frac{1}{2\pi} \int_{-\infty}^{\infty} G(\omega)e^{j\omega\tau}d\omega \]

In the figure 5.1 shows the schematic of FTIR operations and allows measuring the entire spectrum simultaneously. Indeed, on the output if the Michelson interferometer appears the interferogram \( S(t) + S(t + \tau) \). So we can easily get the intensity will differ from the signal intensity \( I(t) = \int S(t)S(t)^*dt \) by the auto-correlation function \( \Gamma(\tau) = \int S(t)S(t + \tau)^*dt \). The Fourier transform of the auto-correlation function gives directly the spectral intensity. The fast and precise mechanical parts of the Michelson interferometer make it possible to do an average over a large number of scans in a reasonable time.
In this work, and FTIR spectrometer has been used for detector characterization. When illuminating the type-II superlattice detector with infrared radiation, photocurrent is generated and a photocurrent spectrum is achieved. A reference spectrum of the photon flux is also measured by a uncooled DTGS detector, which has a responsivity that is essentially equal in the whole spectral range. By dividing the photocurrent spectrum with the photon flux a photo response spectrum is achieved.

Figure 5.1: Schematic of FTIR operations
Measurement setup

As for spectral response measurement, the setup here also has the form of an electro-optical loop in our novel instrument VERTEX 80V. The spectrometer (FTIR) served as an infrared source. Infrared radiation was collected by a parabolic mirror and directed on the sample. Sample was mounted on a cold finger of a helium closed-cycle cryostat and partially was covered with a cold radiation shield. Temperature of cryostat was controlled by Lakeshore temperature controller in 77-300K range. Measured signal was amplified by a preamplifier and was supplied to FTIR for further processing. The light that causes the sample's photocurrent I_{ph} comes from the blackbody with an emissivity close to 1. The temperature of the blackbody is very accurately stabilized at 1000°C.

The sample is connected to the amplifier via the switching matrix and a diode is chosen by the computer. The signal from the diode, as previously stated, consists of the photocurrent I_{ph} and the electrical as well as 300 K background noise. The amplified current of the diode as well as the reference signal from the chopper are plugged into the lock-in amplifier. Finally the detected signal is displayed and sent back to the computer that records the value and switches to the next diode.

Finally, the recorded integrated response data is processed together with the relative spectral response and the spectral responsivity, quantum efficiency as well as specific detectivity of each diode[10] were achieved. In this setup, it is possible to change the temperature of the sample and the applied bias.

Photo detector response

The signal S(t) is not affected by the environment and the measurement system. So the spectrum obtained with the FTIR is a combined measurement of the source irradiance, the beam splitter transmission and the detector response. In addition, the free path in the air causes absorption at several specific wavelengths, corresponding to the chemical composition of the air. In order to minimize the this absorption the FTIR instrument is operated under vacuum.

The background scan figure 5.3A has to be performed prior to the type-II SL detector measurement, the role of which is therefore twofold. For the first, it allows to measure the infrared source irradiance spectrum in order to be able to compare the type-II SL detector to the DTGS reference detector. At the same time, if the DTGS detector is put approximately at the same point as the cryostat containing the type-II sample, it will also register the same free path absorption features as the unknown detector. By dividing one spectrum by the other, we obtain the relative (in order to convert cm^{-1} to µm) type-II response, as it is illustrated in figure 5.2. and 5.3. One can notice that the shape of the obtained spectrum fits well with the absorption formula (equation 3) [11].
Figure 5.2 Sample-6F Photo responses (500 µm mesa) **without DTGS** (background).

Figure 5.3: Background flux at room temperature.
Figure 5.3A: Photo response with wavelength (500 µm mesa, Sample 5C) spectral response of a MWIR type-II photodiode at 78K with DTGS (background).

Since the air composition changes both on a long time scale (e.g. with seasons) and from day to day, especially as far as water and CO$_2$ are concerned, a background scan is needed for every optical measurement. Once the relative spectrum has been obtained, one can proceed to the integrated response measurement in order to obtain the actual quantum efficiency in percents.

**Integrated Response**

The photocurrent is the product of the total incident photonic flux by the external responsivity over the relevant spectrum:

$$I_{ph} = \int_{\lambda} \Phi(\lambda)R_i(\lambda)d\lambda$$  \hspace{1cm} 5.4

The external responsivity $R_i(\lambda)$ is the product of the previously measured relative response $R_{i,rel}(\lambda)$ by the unknown integrated response constant $R_{i,\text{int}}$. The total incident flux is given by:

$$\Phi(\lambda) = M(\lambda,T_{BB})F_{\text{path}}A_{\text{opt}}\frac{\Omega_{BB}}{\Pi}$$  \hspace{1cm} 5.5
Where \( M(\lambda, T_{\text{BB}}) \) is the Plank spectrum, \( F_{\text{path}} \) is the path absorption between the blackbody and the cryostat, \( A_{\text{opt}} \) is the optical area of the device (mesa area minus contact area) and \( \Omega_{\text{BB}} \) is the projected solid angle of the blackbody.

5.3 Results of Optical characterization

The spectral photoresponse of the InAs/GaSb type-II superlattice detectors was measured using a VERTEX spectrometer system. Figure 5.4 shows the photocurrent spectrum of sample 6F (500 µm mesa, purple line) with an onset energy of \( E_g \approx 150 \text{ meV} \). The corresponding samples 5C (500 µm mesa, blue line) and 7G (500 µm mesa, green line) display an onset energy of \( E_g \approx 105 \text{ meV} \). The strong dip is due to absorption of CO\(_2\) in the atmosphere. The temperature was 78 K in all measurements. Because, a high lattice mismatch and thus high interface recombination velocity can have a serious detrimental effect on the performance of optoelectronic devices.

To calculate the absorption coefficient \( \alpha \) for type-II SL is of extreme difficulty especially when ab-initio theories are involved. For the most materials, the absorption coefficient \( \alpha \) increases in the range between 77 K and 300 K.

The bandgap in semiconductors is difficult to calculate using ab-initio theories. But it is relatively easy to measure (e.g. using Fourier spectrometry on a processed device or photoluminescence system). The bandgap dependence on temperature is a well-known fact in all semiconductors. Intuitively, it is clear that the bangap should decrease with temperature. Indeed, from the fact that the lattice parameter increases as consequence of thermal vibrations.
Figure 5.4: (500 µm mesa, Sample 6F, purple line), (500 µm mesa, Sample 5C, blue line) and (500 µm mesa, Sample 7G, green line) spectral response of a MWIR type-II photodiode at 78K.

Figure 5.4 (500 µm mesa, Sample 6F, purple line), (500 µm mesa, Sample 5C, blue line) and (500 µm mesa, Sample 7G, green line) shows photocurrent with photon energy for InAs/GaSb superlattice with a bandgap of $E_g \approx 150$ meV of sample 6F but $E_g \approx 105$ meV of the sample 5C and 7G. This is because the lattice parameter, the bandgap of the Type-II superlattice as function of temperature. The strong dip is due to absorption of CO$_2$ in the atmosphere and since measurements were done using liquid N$_2$ and temperature practically were 78K.
As was mentioned before, a wide range of cut-off wavelengths can be covered with this material system. Figure 5.5 (550 µm mesa, Sample 6F) and 5.6 (170 µm mesa, Sample 5C) shows the spectral responsivity of the device based on InAs/GaSb quantum well structures covering with a 3-14 µm range. So in our case the cut-off wavelength is
~8.5µm.

Figure 5.7: Photo response with wavelength (170 µm mesa, Sample 6F) spectral response of a MWIR type-II photodiode at 78K.

Also in above Figure shows photocurrent with photon energy for InAs/GaSb superlattice with a bandgap of $E_g \approx 150$ meV of the sample 5C and bandgap of $E_g \approx 110$ meV of the sample 6F. Since measurements were done using liquid N$_2$ and temperature practically were 78K. The different bandgap of two samples 5C and 6F; we know, a high lattice mismatch and thus high interface recombination velocity can have a serious detrimental effect on the performance of optoelectronic devices [13].

Thus, it is essential in many optoelectronic devices that the lattice mismatch (strain) and the epitaxial layer thickness be sufficiently small so that misfit dislocations are not generated at the interface; therefore, the lattice constants of multiple layer heterostructures should be matched as closely as possible.
Chapter 6

Electrical Characteristics

6.1 Detector performance: Modeling

The ultimate performance of an IR detector is determined by dark current and excess 1/f noise. Many theses on photodiodes tend to use $RoA$, the resistance-area product at zero bias, as a criterion for comparing diode performance. For diffusion-limited operation, in which $RoA = KT / q J_{\text{dif}}$, the criteria are equivalent; for other sources of current, however, the comparison becomes unnecessarily complicated, and the dark current criterion is much more meaningful. The only real requirement on diode impedance is that it should be large enough so that the detector noise dominates that from the Readout Integrated Circuit (ROIC) [1, 5].

6.2 Dark current in InAs/GaSb diodes

Possible sources of dark current in InAs/GaSb diodes are

i. Thermally generated diffusion current from both sides of the junction;
ii. Thermal generation through band gap states in the junction depletion region;
iii. Generation from the diode surfaces;
iv. Tunnelling in the depletion region via band gap states;
v. Direct tunnelling between the valence and conduction bands in the depletion region.

A model of the thermal and tunnel generated dark currents for 8.5 µm cutoff InAs/GaSb at 78K, utilizing the above parameters for the alloy, is shown in Table 4.1. No distinction is made between the n- and p-regions of the diode, and the trap-assisted tunnelling is assumed to occur through the same Schottky Read (S-R) centers that are responsible for the thermal recombination times. This is a perfectly reasonable assumption InAs/GaSb, due to similarity of the conduction and valence band effective masses, resulting in an intrinsic energy level that is at mid-gap.
In diode, diffusion current is given by

\[ J_{dp} = qn_i^2 \left[ (1/n \tau_n) + (1/p \tau_p) \right] \]

...5.1

where \( \tau_{n,p} = \left[ \left( 1/\tau_{\text{a}} \right) + \left( 1/\tau_{\text{S-R}} \right) \right]_{n,p} \)

where n and p are doping levels on either side of the junction, and \( \tau_n \) and \( \tau_p \) are the limiting minority carrier lifetime.

A member features are apparent. Depletion current dominates even at 78K. The tunnel currents are low, even for the high doping concentration, and should not be limiting current issue even at very low background flux levels. This will even be true for very long cutoff wavelengths. However, the over riding factor in this materials system, as it exists at the present time, is the magnitude of the depletion current, which is turn driven by the S-R lifetime [16].

**Passivation**

Ideally, a good passivation layer must perform three functions:

- Prevent chemical reactions between ambient atmosphere and the semiconductor surface (chemical passivation);
- Eliminate and prevent the formation of interface states in the forbidden gap of semiconductor (electrical passivation);
- Serve as an energy barrier for charge carriers at the interface, i.e. possess a sufficient energy barrier such that electrons will not be lost from the semiconductor surface to the passivating layer.

As described before, a detector based on InAs/GaSb quantum well structures the promising alternative technology to traditional interband infrared materials such as HgCdTe for the near room temperature mid-IR detection. To use these detectors in focal plane arrays their dimensions need to be reduced (\( \approx 20 \mu \text{m} \)). Then surface leakage currents will become a dominant current. To eliminate this effect, the number of surface states has to be minimized.

The performance of SL detector at low temperatures is degraded due to the surface leakage currents. Thus a surface passivation treatment has to be developed for InAs/GaSb material system. Constituent components of InAs/GaSb SL are very chemically reactive. Their surfaces are easily oxidized and a native oxide layer of several nanometers thick is quickly formed upon exposure to air. This leads to surface states in the band gap region.
by modification of surface stoichiometry, and surface roughness. This has a significant impact on the device performance.

In our samples, there are three passivation performed: SiN passivation pattern formation, SiO2 passivation pattern formation on two quarters and wet etching 30 nm GaSb cap layer by selective wet etching.

6.3 Surface generation current

Surface generation currents are typically represented by

\[ J_s = \frac{q n_i s}{2} \]  

where \( s \) is the surface recombination velocity, with no explicit bias dependence and the intrinsic energy level \( n_r = p_r = n_i \). Surface recombination velocity is a term that is used to cover a multitude of possible recombination mechanisms that can occur at the surface of a semiconductor. These mechanisms include:

- Recombination via fast surface states located within the semiconductor band gap at the surface and the recombination through S-R centers located within a depletion region located at the surface of the semiconductor, either thermally or by tunneling.

- Analytical expressions for the surface recombination velocity associated with these transitions indicate that the recombination velocity depends upon the surface potential of the semiconductor [22]. It will be minimal for accumulated surfaces and considerably larger for intrinsic and depleted surfaces.
6.4 Direct tunneling

Direct tunneling between the conduction and valence bands, for a parabolic barrier, in a uniform electric field, with doping N, gives a bias-dependent current.

The tunneling based on a uniform field should give an over-estimate of tunnel current for standard abrupt junction diodes. Allowances for this effect can be made by the inclusion of factor, f, in the exponents in Eqs. 5.4. Modeling suggests that $1 < f < 2$.

The diffusion current from the p-volume is strongly dependent on the metal vacancy concentration. It should be pointed out that the above dark current models allow for performance predictions of any operating InAs/GaSb diode provided that the appropriate S-R lifetimes are defined throughout the unit cell [1, 26].

6.5 I – V measurement

During the I-V measurement, it must make sure that the photocurrent does not affect the total response of the diode. In general, this means that the diodes have to be measured in darkness (with a cold shield that has weak thermal emission at the relevant wavelength). However, for diodes with a long cut-off, the expected thermal noise is high enough to make the diode unsensitive the 300 K background and the use of the cold shield is not always necessary. Figure 6.2.1: Dark Current vs bias voltage (500 µm2 mesa, Sample 5C), Figure 6.2.2: Dark Current vs bias voltage (500 µm2 mesa, Sample 6F) and Figure 6.2.3: Dark Current vs bias voltage (500 µm2 mesa, Sample 7G) features the typical dark current curve and the increase in dark current with bias voltage. All most all sample 500 µm2 mesa 5C, 6F and 7G are 1 mA dark is corresponding bias voltage is 10 mV in both forward and reverse bias operation.
Figure 6.2.1: Dark Current vs bias voltage (500 µm² mesa, Sample 5C) at 78K.

Figure 6.2.2: Dark Current vs bias voltage (500 µm² mesa, Sample 6F) at 78K.
Figure 6.2.3: Dark Current vs bias voltage (500 µm² mesa, Sample 7G) at 78K

Figure 6.2.3A: BLIP condition on $R_0A$ for detectors operating at different frequency range and at different temperatures in a 300 K background
The I-V measurement performed at the Center for Quantum Device provides the current-voltage profile along with the differential resistance given by \( R = \left( \frac{\delta I}{\delta V} \right)^{-1} \). However, a relevant figure of merit of the photodiode should be normalized with respect to the area \( A \). It is also natural to consider this quantity at zero bias, since most of the time it corresponds to the diode operation mode. Therefore, the differential resistance used to describe a photodiode performance is defined through the current density \( J \) as

\[
R_0A = \left( \frac{\delta I}{\delta V_{V=0}} \right)^{-1} \tag{5.5}
\]

The surface dependence of \( R_0A \) can be approximated as

\[
\frac{1}{R_0A} = \left( \frac{1}{R_0A} \right)_{bulk} + \frac{1}{R_{surface}} \frac{P}{A} \tag{5.6}
\]

Where \( (R_0A)_{bulk} \) is the bulk \( R_0A \) contribution (ohm cm\(^2\)), \( r_{surface} \) is the surface resistivity (ohm cm\(^2\)), \( P \) is the diode’s perimeter and \( A \) is the diode’s area. For the diode of infinite size (\( P/A = 0 \)) \( R_0A \) given by equation (5.6) yields the bulk \( R_0A \) value of the material, independent of the surface effects. The slope of the function given by equation (5.6) is directly proportional to the surface-dependent leakage current of the diode.

Figure 6.2.4. The measured \( R_0A \) of the 500\( \mu \)m x 500 \( \mu \)m SLs diode as a function of temperature.
Figure 6.2.4. The autoimmunization achieved for this setup allows controlling the bias voltage and the temperature of the cryostat, measure and exporting the current and the differential resistance and processing the data in order to obtain the current-voltage profile and the $R_0 A$ (500 µm x 500 µm) values for the single diode. The measurement can be done with averaging for very high resistance devices. For the devices with etched mesas, the dangling bonds at the surface of the etched sidewalls are responsible for the increased surface generation-recombination current. Moreover, surface states created by the dangling bonds work as traps for the photo-generated carriers degrading the detector performance. The $R_0 A$ at 294.5 K is 0.04 Ω·cm², but it can be significantly improved by surface passivation.

Figure 6.2.6 Bias voltage vs Dark Current at 78K temperature (170 µm² mesa, sample 6F).
Figure 6.2.7 Bias voltage vs Dark Current at 78K temperature (170 µm² mesa, sample 7G).

Figure 6.2.8 Bias voltage vs Dark Current at 78K temperature (90 µm² mesa, sample 6F).

The above Figure 6.2.5: Dark Current vs bias voltage (170 µm² mesa, Sample 5C), Figure 6.2.6: Dark Current vs bias voltage (170 µm² mesa, Sample 6F), 6.2.7: Dark Current vs bias voltage (170 µm² mesa, Sample 7G) and Figure 6.2.8: Dark Current vs
bias voltage (90 µm² mesa, Sample 6F) features the typical dark current curve and the increase in dark current with bias voltage. All most all sample 170 µm² mesa 5C, 6F and 7G are 1 mA dark is corresponding bias voltage is 10 mV in both forward and reverse bias operation. So the dark current and bias voltage in different sample and different mesa area is all most same nature.

So the main features of the observed I-V characteristics are:

- A much stronger current is obtained for the both positive biased GaSb and negative biased at 78K.

- The current is strongly saturated in the both biased direction in the temperatures 78K. These details of the current mechanism are not completely understood thus far.

Figure 6.2.9: Bias Voltage vs Temp (sample-1)
Chapter 7

7.1 Conclusions

The properties of a mid infrared photo detector, based on InAs/GaSb quantum well structures is type II hetero structure, were investigated. The relatively simple two layer structure shows very promising characteristics for sensitive and dual colour infrared detection. I–V characteristics and spectral response were measured at the temperature range of 78K to 300K. An enhanced optical response with gain larger than unity was observed at 78K.

These hetero structures have a type-II band alignment such that the conduction band of InAs layer is lower than the valence band of GaSb layer. The effective band gap of these structures can be adjusted from 0.4 eV to values below 0.1 eV by varying the thickness of constituent layers leading to an enormous range of detector cut-off wavelengths (3-20µm). The InAs/GaSb SLs have a higher degree of uniformity than the MCT alloys, making them attractive for large area focal plane arrays. They provide a smaller leakage current due to larger effective electron mass, which suppresses tunneling. This material system is also characterized by high operating temperatures and long Auger recombination rates. This suggests the potential for using the SLs technology for realizing high operating temperature devices.

The spectrometer (FTIR) served as an infrared source. Infrared radiation was collected by a parabolic mirror and directed on the sample. Sample was mounted on a cold finger of a helium closed-cycle cryostat and partially was covered with a cold radiation shield. Temperature of cryostat was controlled by Lakeshore temperature controller in 77-300K range.

In the time of optical characteristics measuring system, it was performed significantly that without any bias the sample (diode) showed the immediately saturated, because of more surface leakage current onto the lack of the proper temperature of cryostat. The optical signals are converted into the electrical signal if several conditions are met simultaneously. First, there must be a sufficient generation of carriers at the bulk level which implies that the material has a high absorption. Secondly, the carriers must reach the contacts without recombining.

This is because the lattice parameter, the bandgap of the Type-II superlattice as function of temperature. Since measurements were done using liquid N\textsubscript{2} and temperature practically were78K. A model of the thermal and tunnel generated dark currents for 8.5 µm cutoff InAs/GaSb superlattice at 78K and the performance of SL detector at low temperatures is degraded due to the surface leakage currents. Thus a surface passivation treatment has to be developed for InAs/GaSb superlattice materials system.
In conclusion, the high performance mid-infrared InAs/GaSb quantum well structures detectors ($\lambda$ cut-off was 8.5 $\mu$m at 78K) grown by molecular beam epitaxial operating at room temperature (300K). The structural, optical and electrical properties were characterized using novel instrument VERTEX 80V spectroscopy. In the figure-5.3 (500 $\mu$m mesa, Sample 6F), 5.4 (500 $\mu$m mesa, Sample 5C) and 5.5 (500 $\mu$m mesa, Sample 7G) shows Photo response with wavelength spectral response of a MWIR type-II photodiode of the device in the 3-20 $\mu$m wavelength range at 78K with a zero bias voltage respectively. So that all the samples are notice us, the cut-off wavelength is approximately 8.5 $\mu$m. Also the bandgap in semiconductors is difficult to calculate using ab-initio theories. But it is relatively easy to measure (e.g. using Fourier spectrometry on a processed device or photoluminescence system).

The bandgap dependence on temperature is a well-known fact in all semiconductors. Intuitively, it is clear that the bangap should decrease with temperature. Indeed, from the fact that the lattice parameter increases as consequence of thermal vibrations. We can conclude that the transfer integral corresponding to the s - s interaction decreases and so does the bandgap.

During the I-V measurement, it must be made sure that the photocurrent does not contribute to the total diode current. So the diodes have measured in darkness (with a cold shield that has weak thermal emission at the relevant wavelength). Figure 6.2.1-6.2.3 shows the dark current vs bias voltage for samples 5C, 6F and 7G (500 $\mu$m2 mesas), respectively. The effect of surface passivation on the carrier lifetime and $R_{0A}$ was undertaken.

We can conclude, the time of I-V measurement that the diodes has to the measured in darkness (with a cold shield that has weak thermal emission at the relevant wavelength). The diodes with a long cut-off, the expected thermal noise is high enough to make the diode unsensitive the 300 K background and the use of the cold shield is not always necessary. But it is good if the diode into the cryostat on the temperature at 78K. So we observed in the Dark Current vs bias voltage (500 $\mu$m2 mesa), (170 $\mu$m2 mesa) and (90 $\mu$m2 mesa) features the typical dark current increases with bias voltage. All most all sample 500 $\mu$m2 mesa 5C, 6F and 7G are 1 mA dark is corresponding bias voltage is 10 mV in both forward and reverse bias operation.

Finally, this project work explains how one can access the functional properties of the superlattices by the direct measurements and analysis. A great variety of characterization techniques available and the range of interesting physical phenomena happening in type-II reveal extensive information about the material while helping to satisfy the multilateral demand for high quality infrared systems. The type-II material provides a matchless design flexibility which enables us to tailor both the electrical and optical behaviour.
7.2 Future work

The type II hetero structure (Quantum well structures) detectors are a new promising detection technology. Since it was studying extensively only one decade, physics of this material system was not understood completely yet. Several issues requiring attention are:

Minority carrier lifetime: To date, there is no comprehensive study correlating the carrier lifetime to the structural properties, growth parameters and surface passivation of the SL. Such a systematic study will provide invaluable data such as the minority carrier diffusion length and lifetime and inter sub-band relaxation time that will enable to determine the limiting scattering mechanisms in InAs/GaSb system, such as Shockley Read Hall and Auger recombination.

Detector structure optimization: Based on the known minority carrier lifetime, diffusion length of minority carriers can be determined. This will allow us to optimize absorber thickness of SL detectors, and, in turn, external quantum efficiency.

The future work will include the development of new structures, capable of achieving very high performance in the VLWIR, transfer of the existing technology to alternative cheaper and more conventional substrates, as well as design of novel integrated imaging systems based on focal plane arrays.
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Figure 4.2 Sample-2(6F) Photo response (500 µm mesa)